



RADIOISOTOPE POWER SYSTEMS

RPS-powered Pressure Vessel Mission Concepts for In-Situ Ocean World and Venus Exploration

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POWER TO EXPLORE



Agenda

- Architecture Team (A-Team) Study: RPS-powered Pressure Vessel Mission Architectures for Ocean Worlds and Venus Explorations
 - Study Rationale and Objectives
 - A-Team Study Description
 - Potential Planetary Destinations Considered
 - Explorer Mission Architectures
 - Payload Analysis, Mission Requirements
 - Conclusions and Recommendations
 - Study Participants

Study Rationale

- The NASA RPS Program was interested in studying the use of RTGs within pressure vessels.
 - The notional requirements on RTGs to operate within pressure vessels are not well understood
 - The recent Next-Generation RTG Study¹ left the details of using RTGs in pressure vessels for future work
 - A better understanding of in-situ mission pull for exploration concepts that utilize RPS in a pressure vessel was desired

¹D. F. WOERNER et al, “Next-Generation Radioisotope Thermoelectric Generator Study Final Report,” National Aeronautics and Space Administration (2017).



Objectives of Study

- Understand the in-situ mission concept pull for using RPS in a pressure vessel
 - What is the science justification for in-situ, long-life explorers, that require a pressure vessel, on Ocean Worlds and Venus?
 - What measurements and types of instruments would be needed to realize the science goals?
 - What are the notional mission requirements needed to utilize a Next-Generation RTG in a pressure vessel?
 - Create mission concept architectures for each planetary body to achieve the science goals with the use of an RPS-powered pressure vessel.

Approach of 3-day A-Team Study

- Utilize the JPL Innovation Foundry Architecture Team (A-Team) for collaborative and rapid concept identification
- Session 1 (August 17, 2017): Science and instrument identification
 - Mostly scientists and instruments engineers, plus mission architecture SME
 - Characterize science interest in deep ice, ocean, and Venus exploration; identify sensors and instruments
- Session 2 (August 24, 2017): Mission concept architecture discussion
 - Mostly mission architects and engineers, plus scientist representative from the first session
 - Look at architecture space and identify feasible architectures for each destination considered
 - Determine draft requirements to accommodate RTGs in pressure vessels
- Session 3 (August 31, 2017): Science and mission concept architecture integration discussion
 - All of scientists and mission architects involved in this study
 - Converge on science goals and mission architecture
 - Identify set of architecture options for potential further pressure vessel engineering study

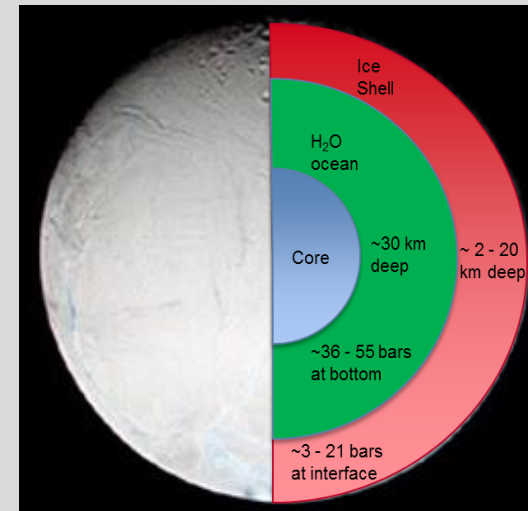
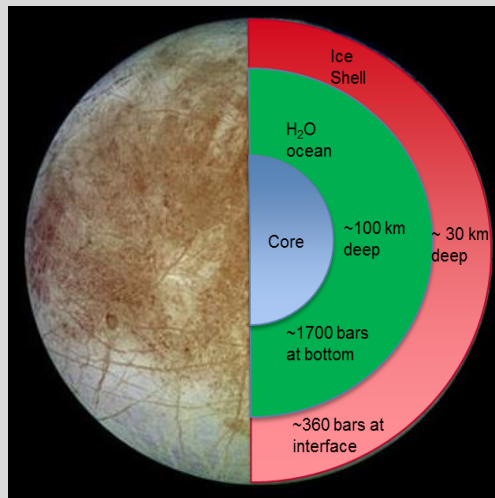


Potential Destinations Considered

- Nine Ocean Worlds (Europa, Enceladus, Titan, Ganymede, Callisto, Dione, Triton, Pluto, Ceres)
 - *All bodies in the solar system which could plausibly have or are known to have a liquid water ocean*
 - Considered explorers for both in the ice shell and in liquid oceans
- Venus
 - Considered explorers for surface missions and low altitude aerial missions
- Mars
 - Considered mission concepts to explore ice at the poles
- The study participants identified science goals for each destination during session 1, but then focused on Europa, Enceladus, Titan and Venus for architecture generation during sessions 2 and 3
 - These destinations were deemed to be the most probable locations for a pressure vessel mission
 - Many science goals and architectures identified during this study are applicable to other Ocean Worlds

Mission Concept Architecture Generation

- Assumptions:
 - Study did not include transport to destination or non-in-situ elements
 - Next-Generation RTG class of RPS is available:
 - Size from 2 to 16 GPHS, higher specific power than currently available RPS
 - Only functions in vacuum
- During session 2, the team explored which areas were technologically feasible to explore and brainstormed dozens of potential concepts within ice shells, liquid oceans, hydrocarbon oceans, and the Venus atmosphere



Example environmental findings, showing estimated surface and subsurface pressures for Europa (*left*) and Enceladus (*right*)

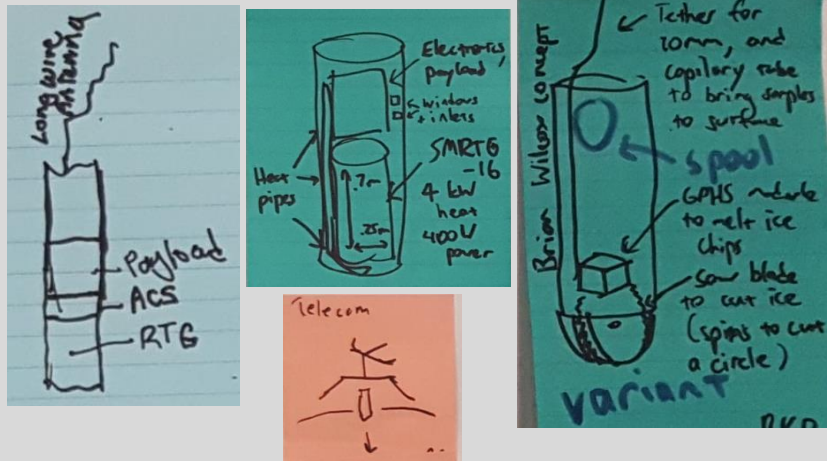
Mission Concept Architecture Convergence

- In session 3, the team narrowed concept focus to the following areas:
 - Ice only (applicable to all Ocean Worlds)
 - Ocean only (applicable to all Ocean Worlds)
 - Titan methane/ethane lake
 - Venus surface
 - Venus aerial
- More detailed concept architectures were identified for the following high science priority areas:
 - Ice only (applicable to all Ocean Worlds)
 - Ocean only (applicable to all Ocean Worlds)
 - Venus surface

Ice Explorer Mission Concept

Multi-year kilometer-scale vertical ocean world ice shell explorer (with Next-Generation RTG power).

Science objectives: Ice shell composition (as a function of depth), D/H ratio, compositional stratification, salinity, porosity, thermal profile, life detection, history deposition



Preliminary mission concept sketches created by the study team

Concept Summary

- Long, skinny aspect ratio $< 2 \text{ m} \times < 30 \text{ cm}$
- Lander could deploy probe and serve as telecom station on surface.
- Could use RPS heat to melt, RPS powered saw, or water jets
 - Would need the ability to navigate through obstacles, such as rocks (cut through or steer around them)
- 3 separate probe attempts to penetrate thick ($> 10 \text{ km}$) layers
 - 1.) Start at Enceladus ($\sim 2 \text{ km}$)
 - 2.) Then go to Europa ($\sim 10 \text{ km}$)
 - 3.) Titan ice layers
- Possible payload:
 - Laser sounder, UV-VIS-IR imager, magnetometer, mass spectrometer, biomolecule detector, hazard avoidance

Challenges

- Constrained volume/surface area may be difficult to find a good thermal control methodology workable from launch to cruise to surface.
- Operation in ultra-low temperature environment ($\sim 100 \text{ K} - 273 \text{ K}$)
- How to get through obstacles (such as rocks)?
- What would happen if the probe enters a water pocket in the ice?
- How to ingest samples in the high pressure environment?
- How to handle telecom through the thick ice?
- How to meet planetary protection requirements (Probability of contamination by one viable Earth microorganism shall be less than 10^{-4})

Requirements on RPS in Pressure Vessel

- May need an RPS qualified for longer life (20+ years) to melt through very thick ice
- Diameter (w/o fins) $< 30 \text{ cm}$
- Must be able to install pressure vessel into RPS at launch site
- Radiation shielding of payload
- Integration cannot compromise the biological cleanliness of the flight system (planetary protection)
- Melt penetration rates are highly dependent on Next-Generation RTG power (need $> 4 \text{ kW}_t$, prefer $\sim 7 \text{ kW}_t$)

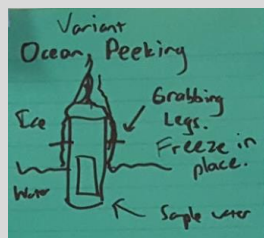
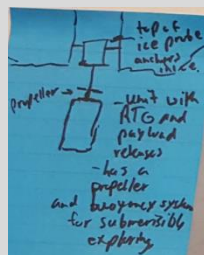
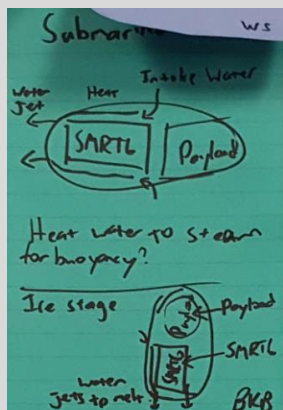
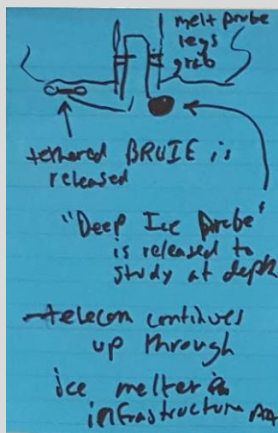
Ice Explorer Concept Payload Power Analysis

- Payload Findings
 - Notional Payload (most sampling every ~15 cm): Laser sounder, UV-VIS-IR imager, magnetometer, mass spectrometer, biomolecule detector (microfluidics, microscope), hazard avoidance (acoustic or radar) (sampling every ~3 m)
- Estimated Mission Concept Power Range
 - Laser sounder: $\sim 10 W_e$, 10 seconds/measurement, 3 measurements/hour
 - UV-VIS-IR imager: $\sim 10 W_e$, 10 seconds/measurement, 3 measurements/hour
 - Magnetometer: $\sim 0.1 W_e$ continuous
 - Mass spectrometer: $\sim 10 W_e$, 10 seconds/measurement, 3 measurements/hour
 - Microfluidics: $\sim 0.1 W_e$, 20 minutes/measurement, 3 measurements/hours
 - Microscope : $\sim 1 W_e$, 1 minute/measurement, 1 measurement/hour
 - Hazard avoidance: $\sim 10 W_e$, 1 minute/measurement, 6 measurements/day
 - Average payload power $\sim 0.5 W_e$
 - Mission driven by electrical/thermal power needed for ice transit
 - $4+ kW_t$

Ocean Explorer Mission Concept

In-situ explorer for within liquid oceans (with Next-Generation RTG power).

Science objectives: Habitability, Life detection, composition, D/H ratio, measure currents, energy balance, depth profile, source of plumes, topography of ocean floor, dissolved gases



Preliminary mission concept sketches created by the study team

Concept Summary

- Different types of architectures are possible (stationary system, buoyant rover, submarine)
- From a science perspective, mobility is preferred (~ 1km vertical and horizontal)
- Minimum 850 hour lifetime in ocean (10 Europa orbits)
- Could carry additional "deep ocean probes" to be dropped and take measurements
- Could communicate through the ice using a tether to the surface or isolated "pucks" that would require a separate power source
- Propulsion options could include propellers or jets
- Possible payload:
 - Mass spectrometer, cameras, sonar, microfluidics, microscope, temperature/pressure sensors, selective ion probe

Challenges

- Needs to be integrated into an ice probe to deliver it to the ocean
- Difficult autonomous navigation, control, and science data acquisition
- How to deal with possible corrosion?
- How to ingest samples at very high pressures?
- Telecommunication through the thick ice would be difficult
- How to meet planetary protection requirements (Probability of contamination by one viable Earth microorganism shall be less than 10^{-4})
- How would the vehicle handle ocean currents?

Requirements on RPS in Pressure Vessel

- Able to withstand extreme pressures (up to ~400 bar at Europa ice/ocean interface)
- Integration of the RPS shall not compromise the biological cleanliness of the flight system.
- Provide survival heat to on board electronics
- Able to withstand environment temperature fluctuations (40 – 273 K)
- Strict dimensional requirements (30 cm diameter, 2 m length)
- Must be able to be integrated on the Launchpad
- Helium byproduct may need to be vented

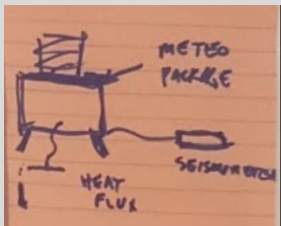
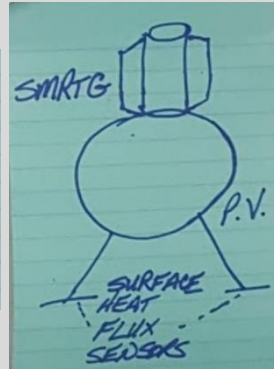
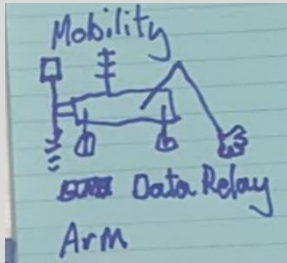
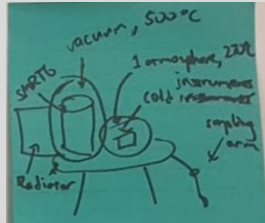
Ocean Explorer Concept Payload Power Analysis

- Payload Findings
 - Notional Payload: Mass spectrometer, cameras, sonar, microfluidics, microscope, temperature/pressure sensors, selective ion probe
- Estimated Mission Concept Power Range
 - Mass spectrometer: $\sim 10 W_e$, 1 minute/measurement, 1 measurement/hour
 - Cameras: $\sim 1 W_e$, 1 minute/frame, 5 frame/hour
 - Sonar: $\sim 10 W_e$, 1 hour/measurement, 1 measurement/day
 - Microfluidics: $\sim 0.1 W_e$, 20 minutes/measurement, 3 measurements/hours
 - Microscope: $\sim 1 W_e$, 1 minute/measurement, 1 measurement/hour
 - Temperature/pressure sensors: $\sim 0.1 W_e$ continuous
 - Selective ion probe: $\sim 1 W_e$ continuous
 - Average payload power: $\sim 2 W_e$
 - Mission driven by electrical/thermal power needed for mobility, telecom, thermal

Venus Surface Mission Concept

Long-lived (greater than one year) Venus surface lander (with Next-Generation RTG power).

Science objectives: Small-scale stratigraphy, seismology, atmosphere and surface composition, long-term weather monitoring, heat flow measurements, energy balance, study superrotation



Preliminary mission concept sketches created by the study team

Concept Summary

- Land a little before local dawn or dusk to minimize risk to diurnal cycle science.
- Direct atmospheric entry w/ drag plate to slow down
 - Perform atmospheric science on descent
- Likely needs an orbiting data relay asset for > ~100 bps telecom
- Some components require active cooling
 - Other components exposed to reduce cooling power, pressure vessel size, and complexity
- Possible Payload:
 - Meteorology package, mass spectrometer, sampling system, seismometer, imager, heat flux relay

Challenges

- Selection of a landing site
- High-temperature electronics robust to the environment
- Remove heat generated by instruments
- Surviving high entry loads (50 – 80 g possible)
- Telecom relay (likely needs an orbiter)
- Volume packing constraints in pressure vessel
- Efficient cooling system for instruments/electronics that cannot be made robust
- Sample acquisitions and transfer

Requirements on RPS in Pressure Vessel

- Needs to handle a cold side temp of at least 550°C (550°C for sufficient ΔT for heat rejection) – heat loops that support sufficient heat exchange
- Withstand entry loads of 50 – 80 g
- High-temperature (1000°C - 500°C) materials must be integrated into Next-Generation RTG configuration
- Thermal control through all phases of the mission (launch, cruise, entry, operations)
- Withstand atmospheric chemistry environment, super critical CO₂
- Next-Generation RTG could potentially be outside of the main pressure vessel if the casing was designed to be a pressure vessel itself

Venus Surface Concept Payload Power Analysis

- Payload Findings
 - Notional Payload: Meteorology package, mass spectrometer, sampling system, seismometer, imager, heat flux relay.
- Estimated Mission Concept Power Range
 - Cooling is a major power driver because it is only 1% efficient in the Venus environment.
 - Meteorology package: $\sim 1 W_e$ continuous
 - Mass spectrometer: $\sim 10 W_e$, 1 minute / sample, 10 samples total
 - Sampling System: $10\text{-}100 W_e$, ~ 30 minutes/sample, 10 samples total
 - Seismometer: $\sim 1 W_e$ continuous
 - Imager: $\sim 1 W_e$, 1 minute/frame, 120 frames total
 - Radiometer for heat flux: $\sim 0.1 W_e$, 1 minute/measurement, 120 measurements total
 - If meteorological package and seismometer need to be cooled, rejecting this heat would cost $\sim 200 W_e$ average over a year. $\sim 300 W_e$ average if parasitic heat from environment is $1 W_t$.
 - Assuming avionics are made robust to operate in Venus environment.

Identified Pressure Vessel

Mission Concept Requirements on RPS (1)

- Planetary Protection
 - Probability of contamination of the ocean by one viable Earth microorganism shall be less than 10^{-4}
 - All flight system hardware that would reach target body shall be protected by a biobarrier prior to launch until reaching target body
 - All flight hardware that would come in contact with the ocean shall be subjected to an overkill vapor H_2O_2 process and protected from recontamination
 - All flight hardware within the PV shall undergo surface and bulk material microbial reduction needed to meet the 10^{-4} probability of contamination requirement (aseptic integration may be required to meet)
 - Integration of the RPS into the flight system shall not compromise the biological cleanliness of the flight system
- Thermal
 - Provide heat for thermal control of pressure vessel interior for Ocean Worlds
 - Next-Generation RTG thermal output needs to be distributed around pressure vessel for Ocean Worlds
 - Thermal output from Next-Generation RTG must not interfere w/ instruments
 - The RPS must provide heat for sample handling instruments for Ocean Worlds. Temperatures (stable) $< \sim 8^\circ\text{C}$ (?) desired. Cryogenic-room temp.
 - RPS may need to be able to operate near heat sources (additional GPHS modules)

Note: Items shown in blue are new requirements that were not called out specifically in the Next-Generation RTG report

Identified Pressure Vessel

Mission Concept Requirements on RPS (2)

- Provide adequate power for vehicle subsystems for all mission modes
- Provide as simple an installation access as possible for the RPS. Could potentially be easily accessible fasteners or rails.
- EM emissions from Next-Generation RTG must not interfere w/ instruments
- Next-Generation RTG radiation cannot interfere/impact instrument measurement or health
- Need to operate for TBD years (potentially 20+ years) to penetrate ice
- Power system must be compact (high W_t / volume ratio) for Ocean Worlds
- RPS dimensions must fit within pressure vessel
- RPS mass < TBD kg
- RPS must allow for removal of fins

Note: Items shown in blue are new requirements that were not called out specifically in the Next-Generation RTG report

Identified RPS-Powered Pressure Vessel Mission Concept Requirements (1)

- ATLO:
 - Unobstructed access to install the Next-Generation RTG horizontally through the launch vehicle fairing & pressure vessel.
 - May need a way of non-cantilever mounting.
 - RPS must comply with DOE shipment requirements.
 - Must allow integration of Next-Generation RTG late in launch flow.
 - RPS must be able to be removed from pressure vessel within TBD hours during ATLO.
 - Cooling requirements on the launch pad.
- Thermal
 - Next-Generation RTG thermal dissipation during cruise.
 - Pressure vessel must reject TBD Watts (depends on RPS) of heat.
 - Provide heat to maintain flight environment -10 to 30 ° C.
 - Must maintain case temperatures ("fin root without fins") between TBD – TBD ° C .
- Total induced dose (TID) of flight electronics, instruments, and materials < TBD (~15 krad) RDML by end of prime science mission.

Note: Items shown in blue are new requirements that were not called out specifically in the Next-Generation RTG report

Identified RPS-Powered Pressure Vessel Mission Concept Requirements (2)

- Pressure Vessel
 - Pressure vessel must maintain gas pressure at < TBD bar to accommodate Next-Generation RTG requirements.
 - Method of regulating internal pressure as temp changes from environment.
 - Pressure Vessel material must be compatible with environment.
 - Sample inlets would need to maintain pressure vessel structural integrity.
 - Ingestion of low temp samples must be able to withstand potential volumetric expansion due to sublimation/phase change.
- Planetary Protection
 - Pressure Vessel shall maintain biological cleanliness of RPS
 - Calibration of the instruments shall not compromise the biological cleanliness of the flight system
- Landing G-load < 25 g to accommodate likely RPS qualifications.
- May need additional radioisotope heat w/o need for electrical power

Note: Items shown in blue are new requirements that were not called out specifically in the Next-Generation RTG report

Conclusions (1)

- Quickly identified three representative mission concept architectures to address ice exploration, ocean exploration, and the Venus in-situ environment.
 - These architectures were chosen considering commonality among RPS-powered pressure vessels in various destinations of interest to the science and mission communities
 - Differences in the environments and ocean depths lead to differences in the specific numbers that would go into requirements for ice and ocean exploration
- Melt probes have significant trades between thermal inventory, ice penetration time, and probe dimensions
 - Findings from Atelier study: Probe carrying an Next-Generation RTG with 16 GPHS can penetrate 10 km of Europa ice within RPS design life only if the pressure vessel can be kept to 1.4 m length and 0.25 m diameter
- Power Level Recommendations:
 - Need a 16-GPHS option for Ice Explorer (and for Ocean Explorer to traverse ice)
 - Venus explorer power requirements strongly sensitive to heat rejection requirements.
 - If all components are robust to Venus environment, could do a mission with $<100 W_e$ (2-GPHS modules).
 - If any components require cooling, mission would require 100-1000+ W_e .

Conclusions (2)

- Identified requirements that may drive Next-Generation RTG design decisions
 - RPS must allow for removal of fins
 - Aspect ratio with fins would make melt probes infeasible
 - RPS may need 20+ year design lifetime
 - Depending on ice thickness and melt rate, missions may take 20 or more years to reach their targets
 - RPS may need additional attachment points for cooling loops
 - Larger heat pipes may be necessary to support sufficient heat exchange to reject to Venus environment
 - RPS may need to be qualified to higher g-loads for entry, decent and landing
 - G-loads to land on Venus are difficult to reduce below 50-80 g. Trade between mission requirements and qualifying the RPS to 50 g.
 - RPS may need special ATLO considerations for integration into pressure vessel
 - RPS may need to be installed into a pressure vessel on a flight system within an aeroshell. Easily accessible attachment points or rails might reduce the complexity. Need to do additional engineering analysis.



Recommendations on Other Future Work

- The following things were identified as recommendations for continuing future work to enable these mission concepts that is not necessarily directly applied to RPS development, but closely coupled:
 - Need to develop ocean worlds instruments
 - Fully utilize analogy to Earth deep sea architecture technology
 - Encourage funding of programs to develop instruments that fit in 30 cm diameter footprint.
 - Encourage funding to develop capabilities for complex autonomy
 - Need improved sterilization technologies and development of sterilizable commercial off-the-shelf hardware
 - Submarine technology development
 - Development of instruments and electronics robust to the Venus environment

Study Participants

- RPS Program Office
 - Young Lee (Client Lead)
 - Brian Bairstow (RPS Systems)
- Engineers
 - Rashied Amini (Systems Engineering)
 - Matt Spaulding (Mechanical)
 - Jason Rabinovitch (Mechanical)
 - Eric Sunada (Thermal)
 - Dave Woerner (RPS Power)
 - Terry Hendricks (RPS Power)
 - Andrew Mitchell (Power Systems)
 - Laura Newlin (Planetary Protection)
 - Aaron Noell (Instruments)
 - Morgan Cable (Instruments)
 - John Elliott (Mission Architecture)
- A-Team
 - Alex Austin (Study Lead)
 - Steve Matousek (Facilitator)
 - Melissa Brown (Logistics)
 - Grace Ok (Documentarian)
- Scientists
 - Bill Smythe (Planetary Science - JPL)
 - Murthy Gudipati (Ocean Worlds - JPL)
 - Robert Hodyss (Ocean Worlds - JPL)
 - Tibor Kremic (Venus - GRC)
 - Zibi Turtle (Titan - APL)
 - Shannon Mackenzie (Ocean Worlds / Titan - APL)
 - Tom Spilker (Ocean Worlds - Consultant)

Questions?

